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Using Evaporative Cooling to enhance thermal comfort conditions in Semi-open Areas.

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Abstract:
The rising global temperatures and increased frequency of heat waves have made it crucial to address the need for effective cooling solutions in semi-open spaces, such as outdoor cafes, large atriums with open ends, stadiums, prayer areas and public transportation waiting areas. The combination of the pedestal fan and mist water spray was introduced to explore the potential of utilizing evaporative cooling as a sustainable and cost-effective method for reducing ambient temperatures within such environments. The experimental study is conducted in a real semi-open environment and the data collection involved air velocity, air temperature, and relative humidity. Two different nozzle configurations were used to define the appropriate arrangement of nozzles and their number to maximize the cooling efficiency. The results showed that the axial air velocity during the mist condition decreased compared to that of the dry condition. The eight-nozzle configuration resulted in a greater reduction in air temperature over the four-nozzle configuration. However, an undesirable increase in humidity ratio resulted. A comparative analysis of the mist plate and mist nozzle revealed that the water particles of comparatively considerable size generated by the mist plate tended to fall within a limited distance without undergoing thorough complete evaporation, thereby failing to provide a sufficient reduction in air temperature. In all cases a distance of three meters from the fan is to be avoided to escape the uncomfortable wetting effect in this region.

Keywords: Evaporative cooling; Thermal comfort; Water mist spray; Mist plate.

1. Introduction:

Outdoor spaces play a crucial role in developing sustainable cities as they provide a conducive environment for pedestrian movement and outdoor recreational activities and significantly enhance urban areas' overall quality and vibrancy [1]. Studying outdoor cooling is gaining importance as it holds the promise of enhancing outdoor availability. Attracting individuals to utilize outdoor and semi-outdoor spaces to provide a pleasant microclimate which provides the potential to enhance the physiological comfort of communities [2]. Spray cooling has recently gained significant global attention due to its beneficial economic and ecological characteristics, making it a widely adopted cooling technique. The objective of using it is to decrease the outdoors ambient temperature and provide a more pleasant climate in highly populated areas subjected to high temperatures [3].

Up to this point, mist cooling systems have encountered testing and implementation mostly in hot and arid regions, where the potential to increase the humidity level is not a major issue for attention. Research has shown the positive impact of these systems in enhancing occupant well-being and cooling outdoor and semi-outdoor environments,[4]. Mist cooling is appropriate for outdoor and semi-external situations since the presence of airflow enhances the rate of evaporation and avoids saturation [5]. A fine mist consists of tiny droplets that have a small size but vast surface area. This large surface area allows for a higher cooling rate. In a moist climate, the evaporation efficiency is crucial as it decreases the quantity of water used for the same level of cooling, hence limiting the corresponding rise in relative humidity that may negatively impact comfort in the surrounding area [6].

The application of water mists is an effective method for enhancing thermal comfort during hot weather, that can be attributed to two primary factors [7]. Firstly, the temperature is reduced as the water mist droplets capture heat from the surrounding air before undergoing evaporation. Secondly, occupants experience a cooling sensation due to wetting their skin and subsequent evaporation effects due to air movement.

The assessment of the spray system's cooling efficiency has incorporated external as well as internal factors. The water supply pressure of the spray nozzle, the nozzle inclination angle and its type, number of nozzle and nozzle height are internal parameters. Conversely, external environmental factors encompass many elements such as wind speed, solar radiation, ambient temperature, and relative humidity within the designated location as mentioned in a review paper by Meng et al. [7].

According to a study conducted by Japanese researchers and validated during the summer Aichi Expo in 2005 [8] it was determined that the spray system has the capacity to effectively lower the ambient air temperature by a range of 1-2 ℃. This reduction in temperature was seen specifically when the initial air temperature exceeded 30℃ and the relative humidity was below 70%,[8], [9].

Huang et al. [3] showed that the temperature decrease, and humidity rise rates vary depending on factors such as pressure, droplet diameter, airflow rate, temperature, and humidity level. Based on these findings, it is strongly suggested to use the spray cooling mechanism (Spray column provided by nozzle) when the nozzle pressure is around 3 MPa. It is suggested to use a suitable nozzle size and spray pressure to decrease droplet size, as it is preferable for the droplet size to remain below 40 μm.

Zheng et al. [10] conducted a study using double-flow pneumatic misting nozzles. The researchers observed that there exists an optimal distance downstream from the nozzle, at which maximum cooling occurs. This optimal distance was determined to be 2 meters downstream from the nozzle. Additionally, it proved that the water temperature has a limited impact on this system. Consequently, there is no need for extra energy to be used to decrease the water temperature before utilization.

Oh et al. [5] in their study, discovered that the addition of a mist system with a higher volume of spraying water resulted in a drop in the air temperature inside the mist-spraying environment, notably by -2.9 degrees. Furthermore, the presence of an air-blowing fan led to a further reduction in air temperature, with a decrease of -3.6 degrees while the mist water droplet size was adjusted to a range of 9–11 μm.

Zhang et al. [11] confirmed that the mist spray system in the urban transportation waiting areas caused a noticeable reduction in air temperature, but it also led to a quite increase in relative humidity. While the maximum and average relative humidity increased by 15.5% and 9.4%, respectively, the maximum and average air temperature declined by approximately 4.67℃ and 2.67℃, respectively. The mist spray system's acceptance rating was 74%, indicating that it might be extensively deployed to enhance summertime thermal comfort in urban transport waiting areas.

As well, Farnham et al. [12] combined sprays and fans to decrease the cooling load in outdoor spaces. The combination of the two was found to rapidly reduce air temperature by 1–2℃, and the wet skin sensation caused by the spray seemed satisfying. Even in relatively humid environments, the mist fan system was able to effectively reduce thermal discomfort. Another study carried out by Farnham et al [13] compared between three hydraulic nozzles operating at two pressures. A nozzle was linked to a high-pressure water pump in each experiment, which supplied either 0.7MPa or 5.5MPa. The results showed that a spray nozzle with a sauter mean droplet diameter of 41 μm could effectively reduce the air temperature by 0.7K without causing wetting. Due to the wet bulb effect on the sensors, the cooling effects of mists with larger droplet diameters induced significant wetting resulting in inaccurate humidity measurements.

Wong and Chong [14] employed a spray system integrated with a fan within an environment characterized by elevated temperatures and humidity levels in Singapore. They proceeded to collect biological samples in containers with the aim of analyzing the development rate of legionella bacteria. The results of the study confirmed that this combination could decrease the air temperature by a range of 1.38 to 1.57℃ and simultaneously raise the relative humidity by a range of 8.61% to 10.38%. However, an elevation in relative humidity has the potential to allow for bacterial and fungal contamination.

The objective of this study is to perform an experimental investigation of the effects of evaporative cooling in semi-outdoor areas to gain more information and verify the effect of semi-outdoor evaporative cooling using a pedestal fan supported with different types of water spraying. It is also intended to map the frontal area of the fan to identify the suitable area for people to sit with a maximum decrease in temperature and achieve the best thermal comfort.

2. Methodology

2.1 Experimental Setup.

In this study, a large size pedestal fan was used to carry out experiments in a semi-open area. The field experiment was conducted in a large passage inside Benha Faculty of Engineering. The space is semi-enclosed, bounded by walls, a roof, and a floor. However, it is exposed to open ends and large windows as shown in Fig.1.

The 0.66 m diameter fan is used in this study. This fan was designed to use a rotating disc of 0.3 m diameter (called a misting plate) in its center. As the water supplied by a submergible pump fixed inside a water tank is delivered to the back of rotating plate, it is centrifugally pushed out radially through multi small passages. As a result, small water droplets are sprayed into the airstream. This action causes the droplets to evaporate as they are carried away by the airstream. The fan centerline was about 1.8 m above the floor.

The fan is capable of rotating at three different speeds, the highest speed of 1350 RPM was found to be the most suitable for producing a high-volume flow rate of air leading to further enhancement of the evaporation process.

The fan airflow was used to spread the effect of air cooling by pushing the water droplets away and enhancing the evaporation of water droplets. The fan could push air to 6 m downstream, but the value of velocity was decreased with increasing axial distance (x) and radial distance (r). The fan was fixed in position during the experiments.

The water spray cooling was carried out by two different methods, the first was by using the misting plate equipped with the fan which forces relatively large water droplets centrifugally into the airstream. The second method was a water mist spray system consisting of a medium-pressure pump (8.6 bar), connected to a ring of nozzles. The nozzles were installed around the periphery of a 0.48 m-diameter ring. The nozzles used in this study were TW3010 (0.3mm orifice), and the water pump used with these nozzles was a Diaphragm Booster Pump (HF-999). The Sauter mean diameter of the water droplets was 20-30 μm as predicted by [15].

2.2 Measuring instruments.

The airspeed was measured using the manual digital anemometer (DAFM3B). The axial velocity was measured as shown in Fig.3. The anemometer velocity range is from 0.5 to 20 m/s with accuracy ±5% and with a resolution of 0.1 m/s.
The air temperature and humidity were measured by the AM2305 sensors. These sensors could sense air temperature between range of -40 to 80 ℃ and with accuracy of 0.3℃. The relative humidity measured by the sensors ranged between 0 and 99 % and with accuracy $\pm$2%.
The water flow rate was measured using the decrease in the water level inside the tank during the period of spraying.

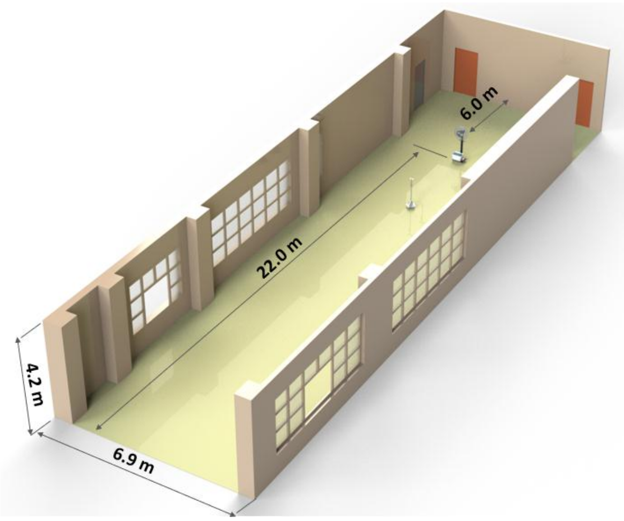


Fig.1: The field of experiment study.

2.3 Test procedure

The air velocity was measured while the spray mode was off to illustrate the velocity pattern. The measurements were in different locations in the axial direction and radial distances from the centerlines of the fan as shown in Fig.3. The axial locations were X=0.6, 1.2, 1.8, 2.4, 3, 3.6, 4.2 and 4.8 m. The radial measurements were taken until the air velocity approached 0.25 m/s. The air volume flow rate was calculated by using the average velocity of two successive measuring points multiplied by the cross-sectional area.
Then the air velocity was measured while using the water mist spray system, starting from 3 m away from the fan to avoid the wetting area with uncomplete evaporation of water droplets, since the humidity measurements were inaccurate.

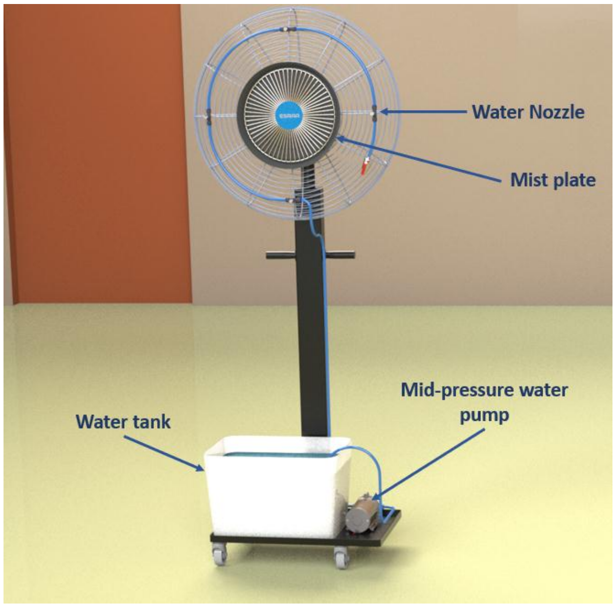


Fig.2: The mist fan component.

The air temperature and humidity upstream of the fan were considered for the initial conditions of the air. The readings of air temperature and humidity were taken when the water spray mode was on, the spray was carried by using two different methods of spraying: one by using a misting plate and the other by using a water mist spray system. Measurements were taken during the summer months between 2021 to 2023.

3. Results and discussion

3.1 Velocity Distribution Under Dry Condition.

The air velocity distribution downstream of the fan was recorded during dry condition to identify the region where the air velocity was effective until the velocity approached zero. The local axial air velocity ($V_{(r,x)}$) in each plane was measured for different radial distance from the centerline of the fan as shown in Fig.4. For the first plane (x=0.6 m), it was noticed that there was a concave near the center due to the presence of the misting plate. The concave vanished gradually as the axial distance increased. The air velocity pattern flattened as the axial distance increased. The air center velocity for the first planes (up to 1.8 m) was about 5 m/s. After that, the velocity gradually declined to 2.4 m/s at the last plane.

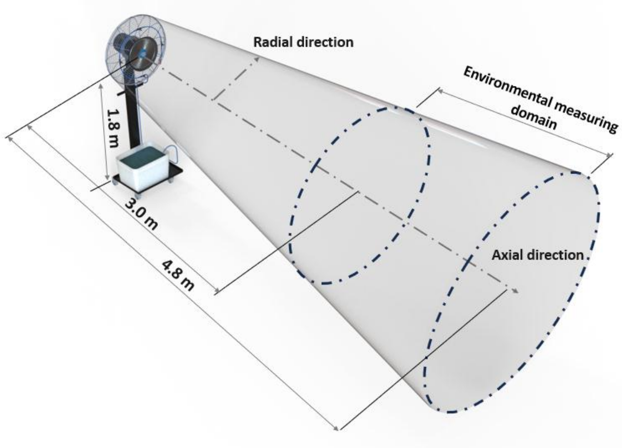


Fig.3: The axial direction (X), radial direction (R) and the environmental measuring domain.

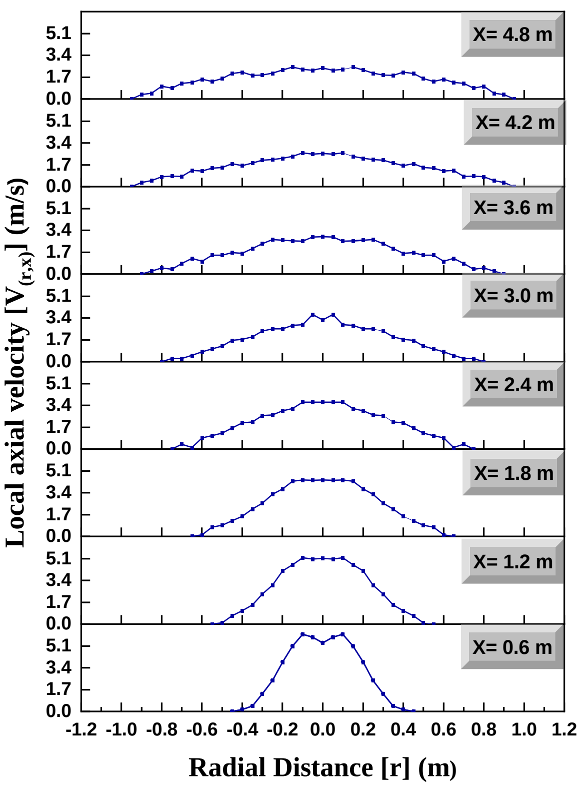


Fig.4: The local air velocity pattern during the dry condition.

The average axial velocity ($\overline{V_x}$)at each plane as presented in Fig.5 decreased approaching a value of 1.5 m/s in the study domain ending at axial distance x=4.8 m from the fan. It's noticed that the radial distance corresponding to a local axial velocity approaching zero ($R_{V_x \to 0}$) increased as axial distance increased. This increase was attributed to the effect of entrained air into the flow region downstream of the fan. The air volume flow rate at any axial distance was calculated by dividing the circular flow area into small rings of thickness (0.05 m), The summation of the flow rate of these rings which are based on the average axial flow velocity passing through the rings resulted in the total flow rate. As a result of entrainment, the air volume flow rate increased by 3 times as the flow passes through the domain.

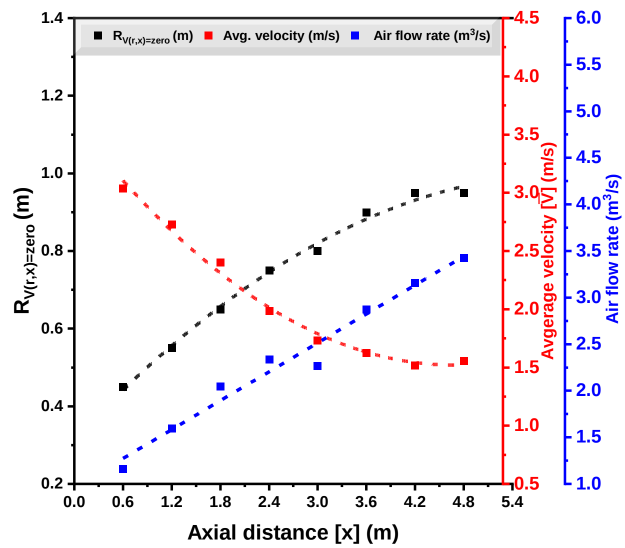


Fig.5: The average air velocity, radial distance of zero velocity and the air flow rate during dry condition.

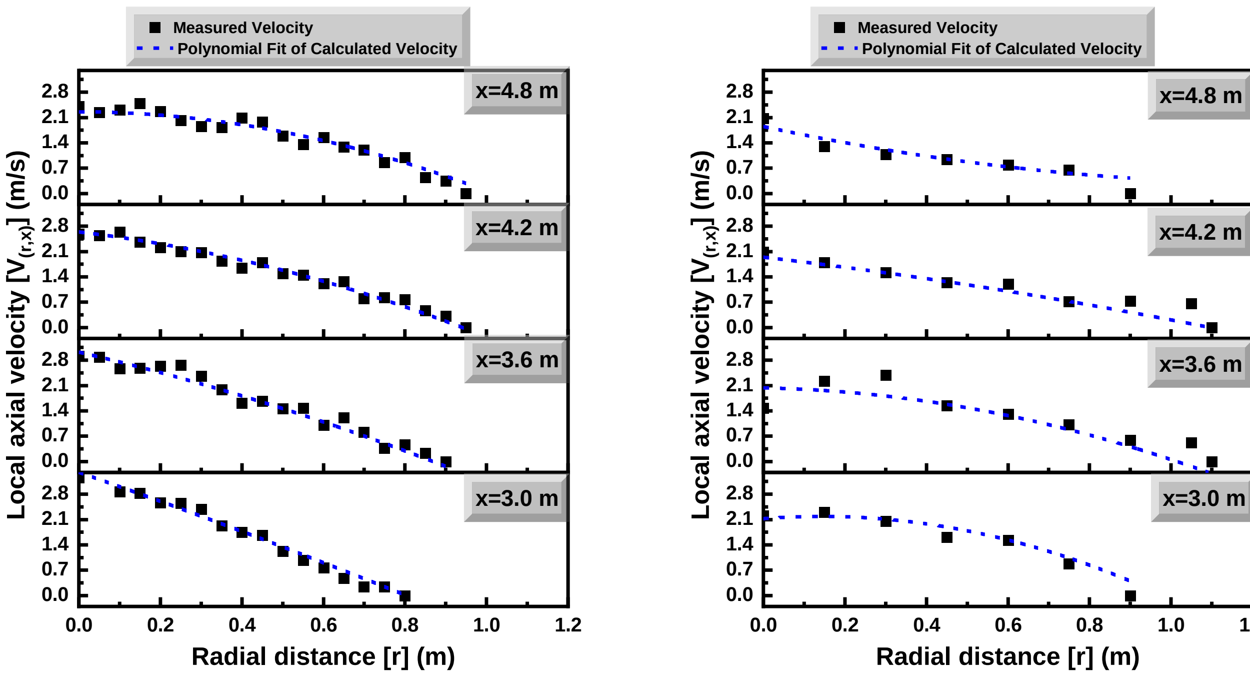
3.2 Comparison of velocity distribution under dry and mist conditions.

The air velocity was then measured when applying mist conditions resulting from the water mist spray system. It was found that the air velocity decreased compared to that of dry conditions as presented in Fig.6. The local axial air velocity decreased while the radial distance corresponding to an axial velocity approaching zero ($R_{V_x \to 0}$) increased. This effect was due to the drag resulting from the presence of water droplets, which increased the turbulence intensity due to interference between the water droplets and the air streams within the domain. It is to be noted that as mist condition was applied aiming at air temperature reduction, extreme wetting was noticed within the first 3 m downstream of the fan. As a result, the measurements concerning air velocity, temperature and humidity were avoided in this region. The presence of occupants in this region should also be avoided.

The equations of the local axial velocity ($V_{(r,x)}$) for dry and mist conditions within the effective domain from 3 to 4.8m were driven statistically as a function of axial distance (x) and radial distance (r) from the experimentally measured values where r and x in meter. The coefficient of determination (R^2) for $V_{(r)}$ driven from the measured values were better than 0.95 for dry condition and better than 0.85 for the mist condition for all dis . As a result, the local axial air velocity at any point downstream of the fan could be calculated easily in the domain of airflow. Equation 1 for the local axial air velocity during the dry condition and Equation 2 for the local axial air velocity during the mist condition of the water mist spray system.

location of x-distances where the measurements were taken, as well as the flow turbulence hindering the accuracy in axial velocity.

The average axial velocity ($\overline{V_x}$) within mist condition in the effective domain ranges from 3 to 4.8 m as shown in Fig.7. This velocity linearly decreased as the axial distance increased. The radial spread of the axial velocity increased to maximum of 1.1 m at x=4.2 m followed by a decline. At the same time the air flow rate increased due to the increase in radial spread which resulted from the air entrainment, after that the trend declined again. This decline could be attributed to errors in velocity measurements as the axial air velocity approached zero near the end of the effective domain.



(a) (b)

Fig.6: The comparison of velocity pattern between two conditions (a) Dry condition (b) Mist spray condition.

$V_{(r,x)} = a_1 + b_1 r + c_1 r^2$ Eq.1

Where; $a_1 = -0.637x + 5.318$ R^2=0.95

$b_1 = 2.168x - 10.436$ R^2=0.97 and

$c_1 = -0.989x + 2.589$ R^2=0.89

$V_{(r,x)} = a_2 + b_2 r + c_2 r^2$

Eq.2

Where; $a_2 = -0.149x + 2.573$ R^2=0.45 ,

$b_2 = -1.834x + 6.387$ R^2=0.81 and

$c_2 = 2.243x - 9.847$ R^2=0.89

It is to be noticed that the coefficients of determinations for the variables corresponding a_1, b_1 and c_1 are very close to one indicating an excellent fit. Meanwhile those of the mist conditions are not very well specially the a_2 variable. This could be attributed to the small numbers of

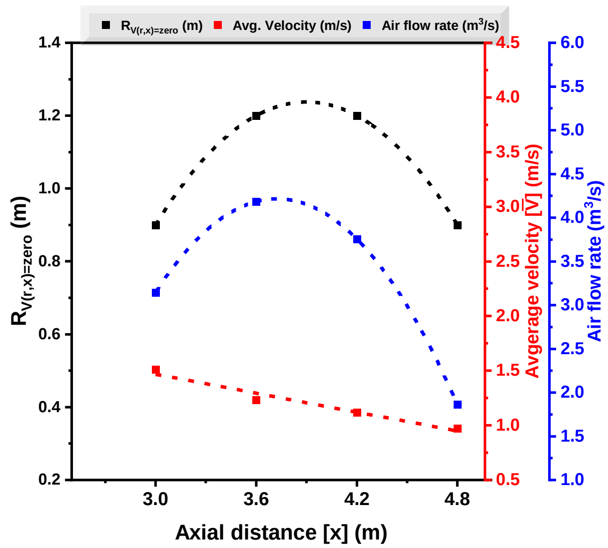


Fig.7: The average air velocity, the radial distance of zero velocity, and the airflow rate during the mist condition.

3.3 Environmental effect of water mist spray system.

The effect of the number of operating spray nozzles was used to study their effect on air temperature and humidity ratio within the effective domain. Two configurations were used, the first consisted of four nozzles spaced by 90°**,** two horizontal and two perpendicular to them with total water supply flow rate of 0.12 L/min. The second configuration consists of eight nozzles arranged at successive 45-degree angles as shown in Fig.8 with total water supply flow rate of 0.24 L/min. These nozzles were located at a diameter of 0.48 m on the fan guard.

The results of air temperature and relative humidity measurements showed the same trend for different days. For comparison between data, days having close environmental conditions were selected.

The results of local air temperature ($T_{(r,x)}$)and local humidity ratio ($HR_{(r,x)}$) which was calculated from local air temperature and relative humidity measurements using psychometric chart. This was done for the two configurations and are presented in Fig.٩. This figure consists of four graphs for the four axial distances within the measuring domain. These results were according to the initial air condition supplied to the fan upstream of approximately 31.2 ℃ and 14.39 (g $_{water}$/kg $_{\mathbf{dry\ air}}$). It is noticed that the local air temperature and humidity values were scattered around an average value for all axial distances within the effective domain. This indicates an equal spread of temperatures and humidity ratios all over each plane. The air temperatures for eight nozzles were lower than those for four nozzles while the humidity ratios for eight nozzles were greater than those for four nozzles as expected.

The average air temperature and humidity ratios were calculated because the local temperatures and humidity were close along the radial direction. Fig.10 demonstrates the variation of the average air temperature and humidity along the axial direction within the effective domain. It is noted that the drop in air temperature below the initial air conditions ranged between 3 to 6℃. The temperature depression was larger for the eight nozzles case. The colling efficiency defined as ($\eta_{cooling}$= [T_i -$\bar{T}_x$]/[T_i-T_{wb}]) was selected to demonstrate the effectiveness of evaporative cooling. It's observed that the cooling efficiency of the eight nozzles configuration was between 51% to 75% which was greater than that of four nozzles which ranged between 20% and 45%.

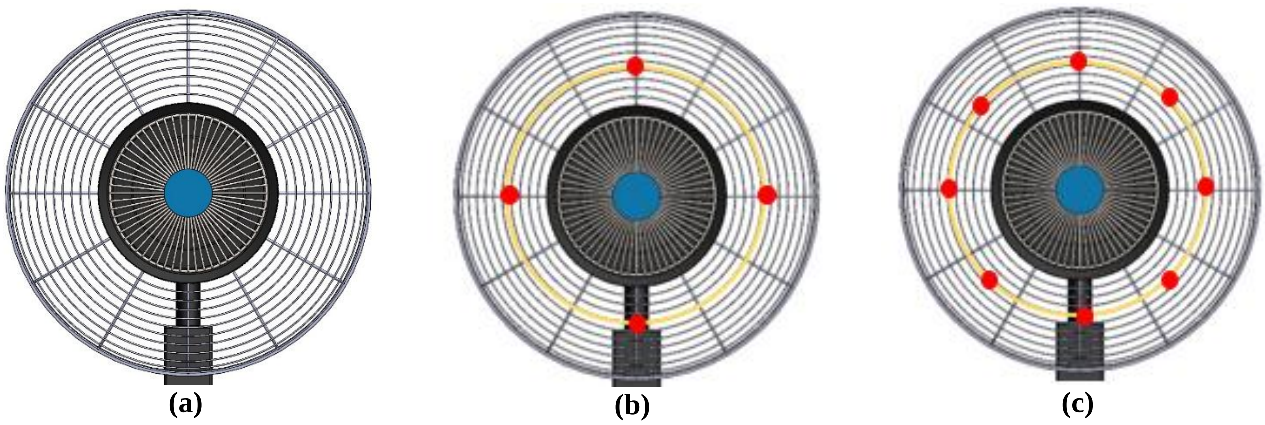


Fig.8: The two different methods of water spraying (a) The mist plate (only). (b) 4-Nozzles configuration. (c) 8-Nozzles configuration.

3.4 Comparison between using the mist plate and the water mist spray system.

Comparing the mist plate with the water four-nozzle mist spray system configurations illustrates the main difference between the two methods. The droplets produced by the mist plate were relatively large compared to that of the mist spray nozzle which caused poor improvement in air conditioning. This comparison was judged by naked-eye observation. The average air temperature and humidity ratio according to two different days of close upstream air conditions supplied to the fan using the mist plate and the four mist nozzles were T_i= 31.65 ℃, HR_{if}= 16.44 (g/kg $_{dry\ air}$) and T_i= 32.6℃ , Hr_i=14.34 (g/kg $_{dry\ air}$) respectively. The results of average temperature, humidity ratio, and cooling efficiency for the mist plate compared to that of the water mist spray system are presented in Fig.11. The average air temperatures for the mist nozzles were lower than those for the mist plate while the humidity ratios for the mist plate were greater than those for four nozzles. As expected, the cooling efficiency of the mist plate was lower than that of the four nozzles, the reason for this decrease in efficiency was the relatively large water droplets produced by the mist plate which needed a longer time to evaporate, and resulted in a relatively large precipitation, as well as the low quantity of water supplied by the small submergible pump (0.03 L/min).

3.5 Thermal comfort improvements.

While thermal comfort is indicated by the predicted mean vote (PMV), this is based on the occupants' satisfaction of many voters, which was difficult to achieve. As an alternative, the effective temperature ET* is used as an indicator of dissatisfaction with the thermal environment (ASHRES 2021)[16].

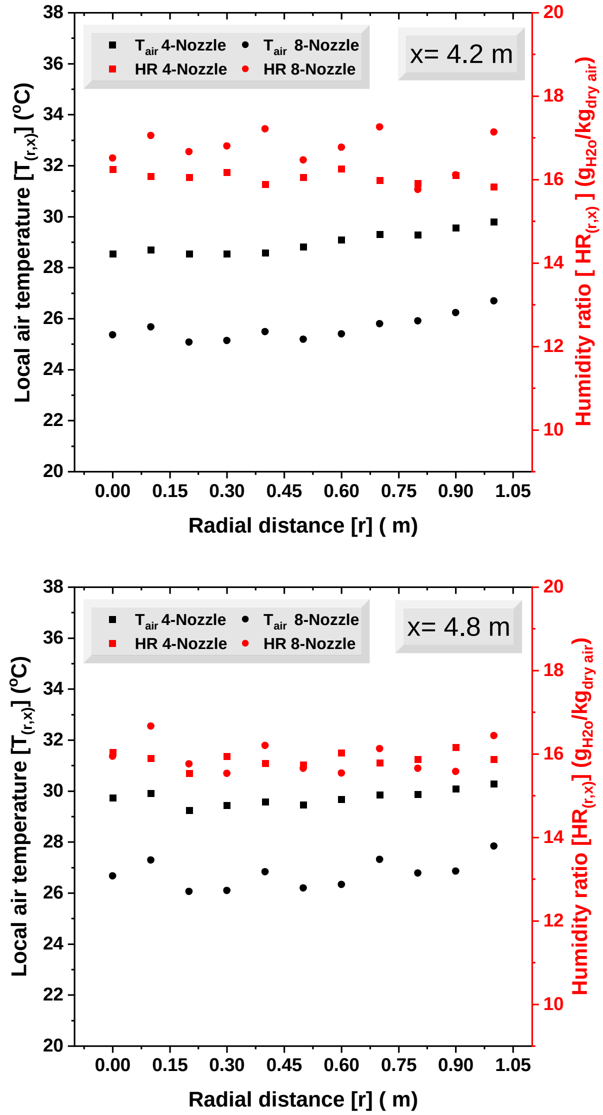
Figure 12 show the psychometric charts indicating the thermal comfort zone. On this figure, the average measured values for the initial conditions as well as the air conditions at 3 m and 5 m bounding the effective domain. These conditions are marked for the mist plate, the 4-nozzles configuration, and the 8-nozzles configuration. From the figures, it is clear that the initial conditions for all cases lay in the slightly uncomfortable zone. The environmental conditions within the effective domain shifted into the comfort zone for the 4-Nozzles and 8-Nozzles configurations. In all cases, air entering the effective domain was cooler than that exiting. It is to be noted that the mist plate improvement did not result in an effective cooling sensation. Meanwhile, the 8-nozzle configuration resulted in better enhancement.

4. Conclusions.

- The study of the air velocity distribution revealed that the utilization of water mist spray resulted in a reduction in the axial air velocity due to the turbulence generated by the existence of water droplets. Conversely, the effective radial distance at which the axial air velocity approached zero was extended.
- As compared to the four-nozzle configuration, the eight-nozzle configuration resulted in a greater reduction in air temperature but an undesirable increase in the humidity ratio.
- It was found that the air conditions were approximately homogenous within the affective domain but suffered from gradual air temperature increase as the end of the domain was approached.
- For the four-nozzle configuration, the loss in calculated air volume flow rate after four meters downstream of the fan was noticed. However, the air conditions' homogeneity persisted. This indicates an error in the axial velocity measurents due to the low accuracy.
- Based on the analysis of air conditions during the mist spray, it was found that the optimal occupancy

area commenced from 3 m downstream of the fan. This was to avoid incomplete evaporation within the initial three meters.

- Compared to the outside air conditions, the optimal occupancy area (3-5 m downstream of the fan) where the air conditions approached the comfort zone.
- A comparative analysis of the mist plate and mist nozzle revealed that water particles of comparatively considerable size generated by the mist plate tended to fall within a limited distance without undergoing complete evaporation, thereby failing to provide a sufficient improvement in air conditions. The use of the mist plate is not recommended by the authors.



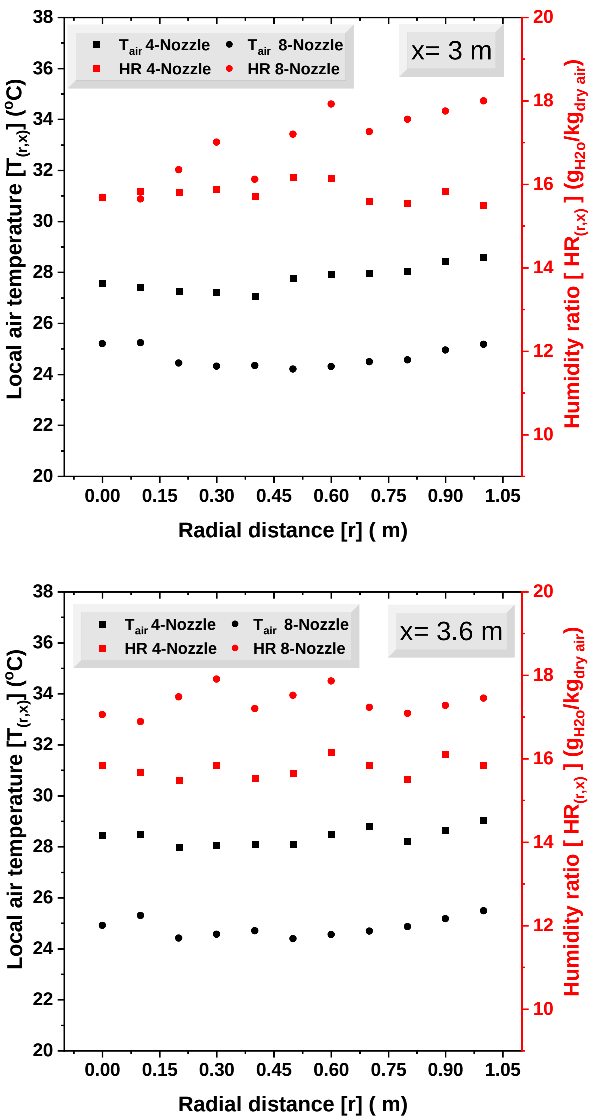


Fig.٩: The local air temperatures and humidity ratios during the mist nozzles spray of two configurations.

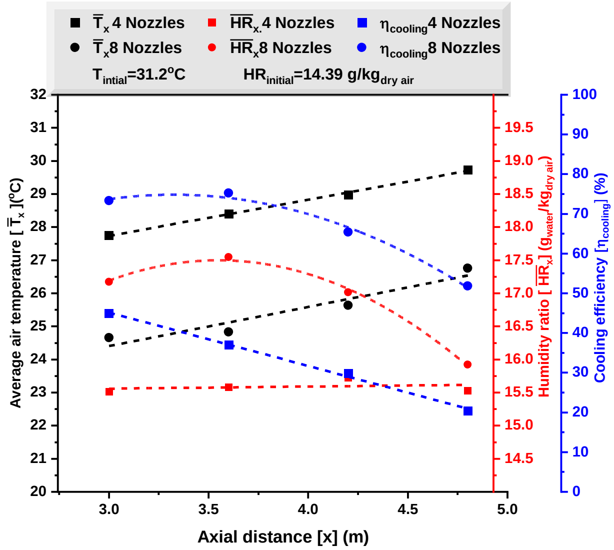


Fig.10: The average air temperatures, humidity ratios, and the cooling efficiency during the mist nozzles spray of two configurations at various axial distances.

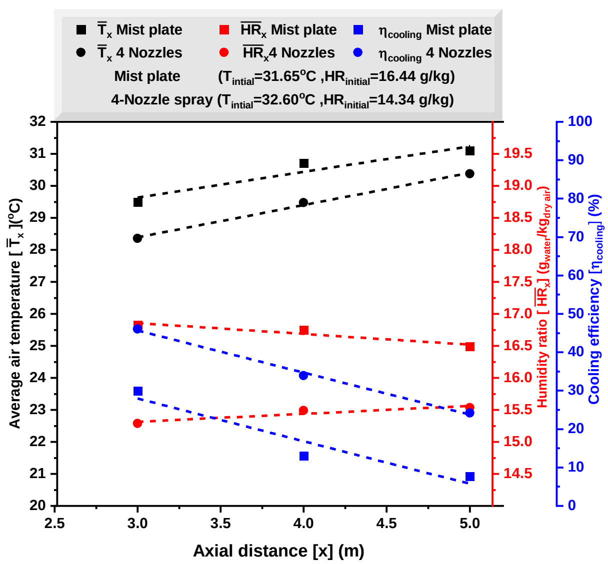


Fig.11: The average air temperatures, humidity ratios, and cooling efficiency during using the mist plate and the mist nozzle spray at various axial distances.

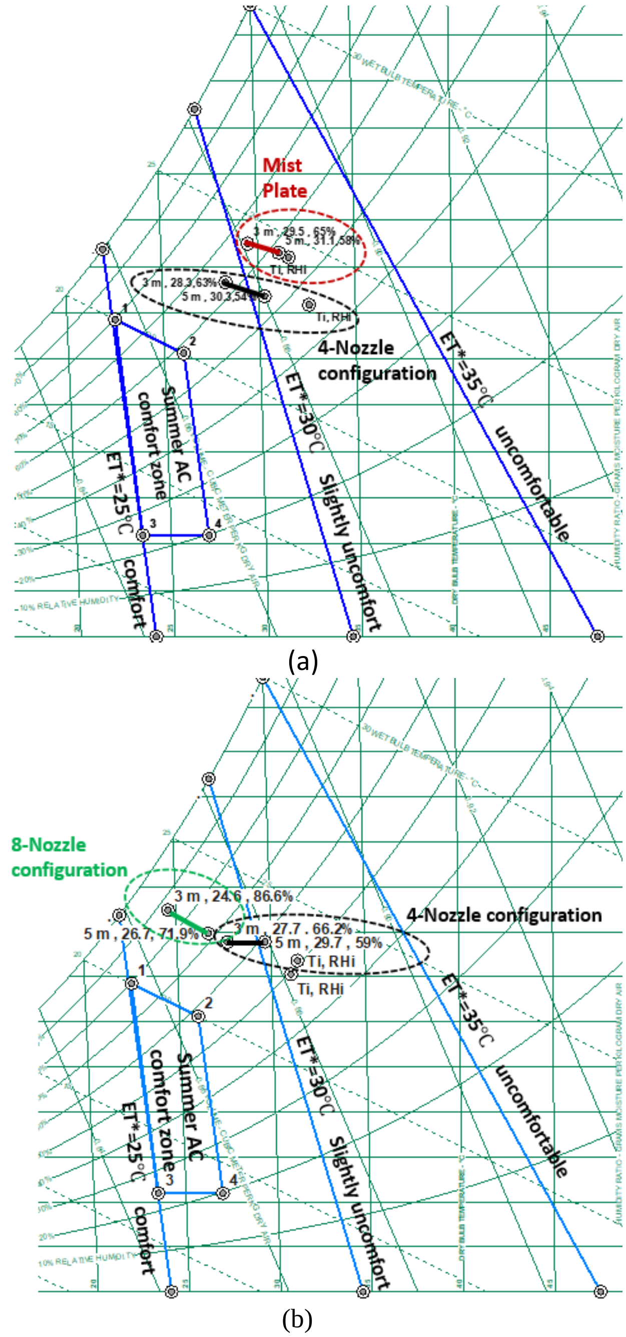


Fig.12: The effective temperature ET* lines as an indicator of thermal comfort and the enhanced mist conditions. (a) Comparison between the mist plate and 4-Nozzles configuration. (b) Comparison between 4-Nozzles and 8-Nozzles configuration.

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